Coordinated Start and Automated Vehicle Platoons for Arterial Intersection Improvement to Solve the Capacitated Vehicle Routing Problem

Ngoc Anh Cao
University of Economics - Technology for Industries, Hanoi, Vietnam | VNU Information Technology Institute, Vietnam National University, Hanoi, Vietnam
cnanh@uneti.edu.vn

Tran Bich Thao
University of Economics - Technology for Industries, Hanoi, Vietnam
tbthao@uneti.edu.vn

Ngo Sy Dong
Vietnam Electric Power University, Hanoi, Vietnam
dongns@epu.edu.vn

Pham Huu Truyen
Vinh University of Technology Education, Vinh, Vietnam
phtruyen2019@gmail.com (corresponding author)

Nguyen Viet Hung
International Training and Cooperation Institute, East Asia University of Technology, Hanoi, Vietnam
hungnv@eaut.edu.vn (corresponding author)

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ABSTRACT

Road intersections often serve as critical congestion points along urban arterials, leading to a reduction in roadway capacity. Intelligent Transportation Systems (ITS) have been employed to enhance traffic flow and mitigate urban congestion, serving as a solution to address the Vehicle Routing Problems (VRPs) impacted by various incidents, which can range from severe to non-severe. This study proposes a novel method that leverages platooning within automatic car-following systems for vehicles stationary at red traffic signals. The method enables coordinated acceleration as the signal transitions to green, allowing a greater number of vehicles to pass through the intersection during a single green phase compared to conventional, manually driven vehicles. To evaluate this approach, a new simulator tailored for connected vehicle applications was developed to design and assess the performance of Cooperative Adaptive Cruise Control (CACC) platoons. Numerical simulations indicate that the proposed CACC-based strategy significantly enhances traffic mobility and intersection throughput.

Keywords-arterial intersection; Advanced Driver Assistance Systems (ADAS); coordinated start; connected vehicles; car platooning

I. INTRODUCTION

The rapid growth of urbanization and the widespread adoption of automobiles have greatly intensified traffic congestion, creating significant challenges for urban management [1, 2]. Signalized intersections, as critical nodes in transportation networks, play a pivotal role in addressing Vehicle Routing Problems (VRPs), which involve determining the optimal route for a fleet of vehicles [3, 4]. Consequently, the optimization of traffic flow at signalized intersections has received considerable research attention [5, 6].

While traffic lights play a crucial role in ensuring safety on urban roads [7], they also introduce recurring vehicle acceleration and deceleration cycles due to the stop-and-go nature of red and green phases, which leads to traffic shockwaves, elevated congestion, increased fuel consumption, and higher pollutant emissions [8]. Furthermore, the mixed traffic environment is inherently more dynamic due to the diverse range of vehicle maneuvers, pedestrian activity, and commercial and residential driveways.

To address these challenges, Intelligent Transportation Systems (ITS) have emerged as promising tools for optimizing traffic capacity, alleviating congestion, and enhancing road safety [9]. These systems leverage automation and wireless communication in connected vehicular environments [8], with Connected and Automated Vehicles (CAVs) offering the potential to improve efficiency, safety, and sustainability at signalized intersections [7, 10]. Communication systems can offer several advantages for traffic flow in arterial sections, including enhanced vehicle movement efficiency, reduced travel time, decreased fuel consumption, and lower emissions. For example, access to traffic Signal Phase and Timing (SPaT) data enables infrastructure to compute optimal vehicle speeds, allowing equipped vehicles to pass through intersections without stopping [6, 11].

Cooperative Adaptive Cruise Control (CACC) is a core ITS application that integrates automated speed and spacing control with cooperative communication technologies, including vehicle-to-vehicle (V2V) and infrastructure-to-vehicle (I2V) data exchange [6, 12]. V2V communication transmits real-time data about leading vehicles, while I2V provides critical information such as variable speed limits and SPaT, enabling synchronized vehicle responses. This supports scenarios where CACC-equipped vehicles halted at red lights can accelerate in coordination when the signal turns green [4]. Research in [13] showed that such vehicle platooning significantly enhances intersection throughput, supported by queuing models demonstrating capacity gains. Related studies, such as in [14, 15], have proposed multi-agent coordination models where autonomous vehicles and intersections act as intelligent agents, employing reservation-based strategies to manage traffic flow. The work in [16] extends these models by incorporating connected vehicle technology, enabling vehicles to dynamically form platoons.

This study focuses on implementing an "arterial coordinated start" strategy, in which CACC-equipped vehicles form a platoon while waiting at a red light and then accelerate simultaneously once the signal turns green. This synchronized start allows more vehicles to clear the intersection within a single green phase compared to manually driven vehicles. The control strategy ensures that each vehicle in the platoon maintains a safe following distance, adjusted dynamically based on speed. The lead vehicle operates under conventional Cruise Control (CC), tracking a time-varying reference speed post-green signal, and transmits this speed to following vehicles via a feedforward controller. To design and evaluate this approach, a new simulation environment tailored to connected vehicle applications was developed. The simulation results demonstrate that the proposed CACC-based platooning strategy significantly improves intersection mobility, an essential advancement for addressing VRPs in urban traffic networks.

II. LONGITUDINAL VEHICLE DYNAMICS

To design the control algorithm for Advanced Driver Assistance Systems (ADAS), the longitudinal vehicle dynamics model is employed [14]. The governing equation describing longitudinal vehicle motion is given by:

$$m_v \dot{v}(t) = \bar{F}_x - F_A - F_G - F_R \qquad (1)$$

where m_v indicates the vehicle mass, $v(t)$ is the forward velocity, $\bar{F}_x$ is the traction or actuation force generated by the engine and drivetrain: $F_A$is the aerodynamic drag force, F_R is the gradient resistance, and F_G is the rolling resistance.

Since (1) is nonlinear in the forward velocity $v(t)$, it can be linearized using a first-order Taylor approximation around an equilibrium point $(v_0,\ F_0)$, where $\bar{v} = 0$. At equilibrium (the forces are balanced, and the traction force becomes:

$$\bar{F}_{x0} = \bar{F}_{A0} + \bar{F}_{G0} + \bar{F}_{R0} \qquad (2)$$

where $\bar{F}_{x0}$ can be determined by assuming appropriate values for $v_0,\ m_v$.

After linearization, the perturbed system can be expressed in state-space form as:

$$\dot{v} = -\frac{1}{\zeta_v} v + \frac{K_v}{\zeta_v} F_v \qquad (3)$$

where the perturbed variables are determined as:

$$\zeta_v = m_v / (\rho_D C_D C_R v^2) \qquad (4)$$

$$K_v = 1 / (\rho_D C_D C_R v^2) \qquad (5)$$

where ζ_v is the vehicle's time lag constant, and K_v is the vehicle gain, ρ_D is the air density, C_D is the air drag coefficient, C_R is the modified resistance coefficient.

III. METHODOLOGY

A vehicle equipped with the CACC system can use V2V communication to transmit its speed to the following vehicle or receive the speed of the preceding vehicle. When the CACC system is further equipped with I2V communication, it can also receive information about the current and upcoming traffic signal phases. This enables the lead vehicle in a platoon to be informed in advance of the transition from red to green. Upon receiving the signal change information, the platoon can initiate coordinated acceleration as soon as the light turns green. This synchronized movement allows all vehicles in the platoon to accelerate smoothly and simultaneously, reducing response delays and improving the throughput of the intersection. Such coordination minimizes shockwaves, shortens start-up lost time, and enhances overall traffic flow efficiency.

We consider a scenario where a platoon of sedan-type vehicles equipped with CACC capabilities is halted at a signalized intersection, awaiting a green light, as illustrated in Figure 1. The platoon consists of n CACC-equipped vehicles, where $z_i(\ i = 1,\ldots,n)$ represents the positions of the follower cars, z_l denotes the position of the lead car, and L_v is the length of a vehicle.

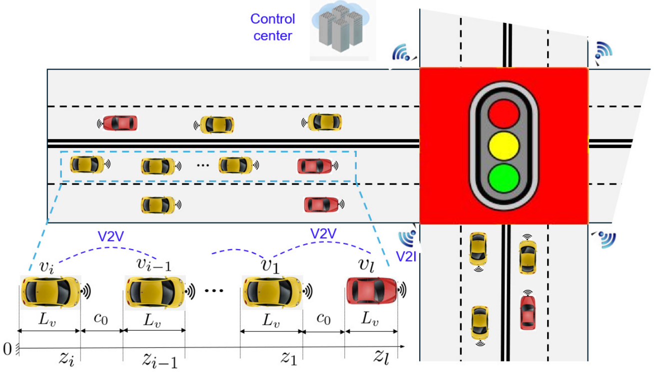

Fig. 1. Consecutive cars in a platoon are stopped waiting for the traffic light to turn green.

The distance between the cars in the platoon when stationary is denoted as c_0, which represents the desired standstill spacing. This distance is measured using onboard sensing devices or external measurement tools. Once the traffic light transitions to green, the leader vehicle receives this signal via the I2V communication system and promptly begins to accelerate to reach the maximum allowable speed as quickly as possible. As the leader accelerates, the follower vehicles within the platoon also accelerate in synchronized motion, while maintaining a safe inter-vehicle distance. This safety distance serves as the reference for the distance control system in each follower vehicle. The desired inter-vehicle distance for the i$^{\text{th}}$ vehicle is defined by the following equation, as proposed in [17]:

$$d_i^{ref} = c_0 + h_i v_i + \frac{v_i^2}{2D_i^{max}} - \frac{v_{i-1}^2}{2D_{i-1}^{max}} \tag{6}$$

where h_i is the desired headway time for the i$^{\text{th}}$ vehicle, v_i and v_{i-1} are the velocities of the i$^{\text{th}}$ (controlled) and (i-1)$^{\text{th}}$ (preceding) vehicles, respectively, and D_i^{max} and D_{i-1}^{max} are the maximum deceleration capabilities of the i$^{\text{th}}$ and (i-1)$^{\text{th}}$ vehicles, respectively.

A. CC System Design for the Lead Vehicle

In the first-order vehicle model (3), the system input is the tractive force, which is generated by the throttle actuator. The throttle actuator is modeled as a Direct Current (DC) servomotor, capturing its dynamic response to control inputs. To develop a more realistic vehicle representation, the CC system incorporates the transfer function of this actuator, which adjusts the throttle angle. The actuator dynamics are characterized by a second-order transfer function, defined as follows [18]:

$$\varXi_a(s) = \frac{F_{vl}}{u_l} = \frac{K_a}{s(\zeta_a s+1)} \tag{7}$$

where u_l denotes the motor duty cycle (expressed as a percentage), serving as the control input for the lower layer. K_a and ζ_a represent the actuator's gain and time constant, respectively. The output of the actuator, the throttle opening angle, can be directly translated into the tractive force F_{vl}. In essence, the degree of throttle opening determines the power output and resulting tractive force, which initiates vehicle motion.

Inspired by the models in [14, 19], the actuator and vehicle parameters are assumed as follows: $K_a = 100\ Ns/\%$, $\zeta_a = 0.005\ s$, $\zeta_v = 100\ s$, $K_v = 0.0075\ m/Ns$.

The overall plant transfer function for the CC system is derived by cascading the throttle actuator transfer function with the vehicle dynamics (3) and (6), resulting in:

$$\varXi_l(s) = \varXi_a(s)\varXi_v(s) = \frac{K_a K_v}{s(\zeta_a s+1)(\zeta_v s+1)} \tag{8}$$

In this closed-loop system, the reference input is the desired vehicle velocity. A Proportional–Integral–Derivative (PID) controller is employed to regulate this system, with a transfer function defined as:

$$\varXi_{PID}(s) = K_P + \frac{K_I}{s} + K_D s \tag{9}$$

To achieve specific pole placement for system stability and performance, the PID controller gains are selected based on the tuning approach from [14, 20], with the parameters expressed as:

$$K_P = \frac{0.34(\zeta_a+\zeta_v)-0.3\zeta_a\zeta_v}{K_a K_v} \tag{10}$$

$$K_I = \frac{0.04(\zeta_a+\zeta_v)-0.04\zeta_a\zeta_v}{K_a K_v} \tag{11}$$

$$K_D = \frac{\zeta_a+\zeta_v-0.66\zeta_a\zeta_v-1}{K_a K_v} \tag{12}$$

B. CACC System Design for the Follower Vehicles

In a CACC system, follower vehicles are required to track the motion of a leader vehicle while maintaining a safe inter-vehicular distance, as defined by (5). The closed-loop system of each follower vehicle comprises two primary components: i) a feedback sub-controller $F_{fb,i}$, which is responsible for maintaining the desired inter-vehicle distance by reacting to relative position and velocity, and ii) a feed-forward sub-controller $F_{ff,i}$, which is designed to compensate for measurable disturbances, such as the acceleration or deceleration of the preceding vehicle.

To address the potential failure in V2V or V2I communication, a robust ACC controller with dual integral action is adopted. This controller is suitable because it assumes that the speed of the preceding car can be modeled as a ramp-type signal. Consequently, the proposed controller is capable of ensuring accurate tracking even under substantial acceleration or deceleration events of the lead vehicle.

The state-space model for vehicle i, incorporating the dynamics from (3) and a double integrator for error tracking, is formulated as:

$$\begin{cases}\dot{x}_1 = \dot{z}_i = v_{i-1} - x_2 \\ \dot{x}_2 = -\frac{1}{\zeta_v} v_i + \frac{K_v}{\varsigma_v} F_{Vi} \\ \dot{x}_3 = d_i^{ref} - x_1 \\ \dot{x}_4 = x_3 \\ y_{iz} = z_i + b_i v_i \end{cases} \Rightarrow \begin{cases}\dot{x}_i = A_i x_i + b_i F_{vi} \\ y_i = [1 \quad 0 \quad 0 \quad 0] x_i \end{cases} \quad (13)$$

where $x_1 = z_{i-1} - z_i$, $x_2 = v_i$, x_3 is the integral of distance error and x_4 is the dual integral of error in closed loop.

Therefore, the controller incorporating the two components can be expressed as follows:

$$F_{vi} = F_{fb,i} + F_{ff,i} = -K_i x_i + \Xi_{ff}(s) v_{i-1} \quad (14)$$

where $K_i = [k_1 \quad k_2 \quad k_3 \quad k_4]$ is the state feedback gain matrix, $x_i = [x_1 \quad x_2 \quad x_3 \quad x_4]^T$.

To compute the optimal control input $F_{fb,i}$ a quadratic performance index is minimized:

$$J(x_i, F_{fb,i}) = \int_0^\infty (x_i^T Q x_i + F_{fb,i}^T R F_{fb,i}) d\tau \quad (15)$$

where $Q = Q^T \geq 0$ and $R = R^T \geq 0$ are symmetric, positive definite weighting matrices. To counteract measurable disturbances, particularly the velocity of the preceding vehicle, the feed-forward sub-controller is implemented as: [19]:

$$\Xi_{ff}(s) = \Xi_v^{-1}(s) \quad (16)$$

However, since $\Xi_v^{-1}(s)$ is generally non-causal and unrealizable, an approximate inverse is used:

$$\Xi_v^{-1}(s) \approx \frac{1 + s\zeta_v}{K_v(1 + s\zeta_v/\xi)} \quad (17)$$

where ξ represents the effective frequency range over which the approximation remains valid.

IV. RESULTS AND DISCUSSION

To analyze the performance of the traffic flow of vehicles with and without the CACC system, a comparative simulation was conducted at a signalized intersection. For the simulation, we considered $n = 20$ cars, with the platoon's parameters of $c_0 = 2\,m$, $L_v = 5\,m$, $D_i^{max} = 5\,m/s^2$, $v_{ref} = 14\,m/s$ or $v_{ref} = 50\,km/s$. The first 10 cars are simulated as autonomous cars while the last 10 as manually driven. For autonomous driving, a short headway time (h_i) of 0.75 s is examined, and for cars operated manually, a longer headway time h_{i_out} of 2.0 s examined [21]. The lead car sets its velocity according to the green light phase received via the I2V system and transmits this information to the first follower using the V2V link, which has a channel delay of 100 ms [6]. Each subsequent follower uses the velocity data from the preceding car to correct disturbances via a feed-forward controller. Each follower employs two controllers: i) the ACC controller which is implemented using a Linear Quadratic Regulator (LQR), with the state feedback gain matrix $K_i = [6{,}840 \quad -4{,}181.3 \quad -5{,}573.4 \quad -1{,}974.7]$, and ii) the CACC controller which incorporates a feed-forward component based on an approximate inverse of the vehicle dynamics derived from (13). Initial vehicle positions are determined using:

$$z_l^0 = (n+1)L_v + nc_0$$

$$z_i^0 = (n - i + 1)L_v + (n - i)c_0, \quad i = 1, \ldots, n \quad (19)$$

The simulation experiment is divided into two phases:

- Phase 1 (0–30 seconds): The reference velocity is set to zero, representing the red-light phase, during which all vehicles in the platoon remain stationary at the intersection.
- Phase 2 (t ≥ 30 seconds): The traffic signal turns green, and the reference velocity for the lead vehicle is set to 50 km/h, initiating movement of the entire platoon.

Simulation results, as shown in Figure 2, depict the inter-vehicle distances maintained through ACC/CACC controllers, which regulate spacing between consecutive vehicles. Figure 3 illustrates the velocity profiles of both autonomous and manually driven vehicles within the platoon. From these figures, it is evident that the autonomous vehicles exhibit shorter settling times and maintain tighter spacing compared to manually driven vehicles, which require larger time headways for safety.

Figure 4 evaluates platoon performance during a 30-second green light interval. To clear the intersection, the platoon must travel a minimum of 148 meters, comprising the platoon length and a 10-meter road width perpendicular to the direction of travel. Results indicate that the last four manually driven vehicles fail to clear the intersection in time due to increased inter-vehicle spacing caused by human driving behavior. In contrast, when all 20 vehicles in the platoon are autonomous and interconnected via the CACC system, Figure 5 confirms that all vehicles successfully pass through the intersection within the 30-second green light period. This coordinated movement enhances string stability and reduces start-up delays, allowing a greater number of vehicles to traverse signalized intersections. Consequently, full automation in platoons can significantly improve traffic flow efficiency and increase the capacity of urban arterial intersections.

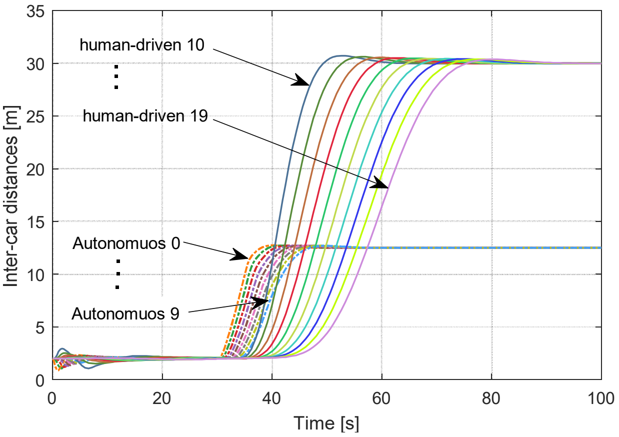

Fig. 2. The inter-car distances in the platoon.

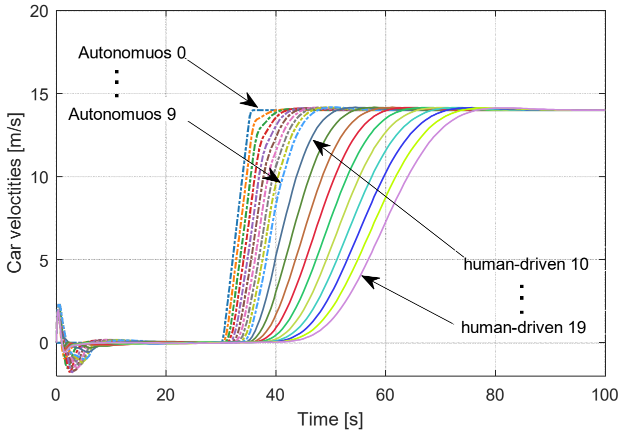

Fig. 3. Car velocities in the platoon.

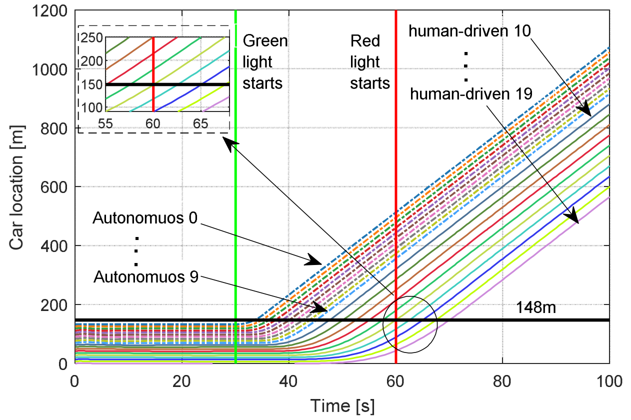

Fig. 4. Car location in the platoon (10 autonomous-10 manually driven).

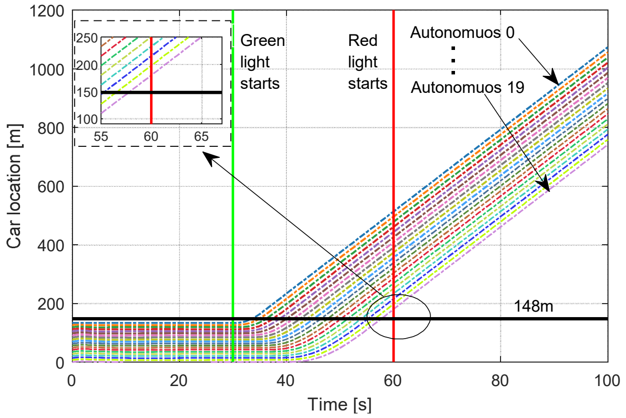

Fig. 5. Car location in the platoon (20 autonomous).

V. CONCLUSION

This study presents an approach to enhance the car throughput at traffic-light-controlled intersections during the active green signal phase. The proposed method involves organizing vehicles into a string formation, each equipped with a Cooperative Adaptive Cruise Control (CACC) system. This configuration enables synchronized vehicle movements, including acceleration and deceleration, which significantly reduces the time required for vehicles to traverse the intersection. Upon the activation of the green light, the lead vehicle receives a signal from the traffic light, facilitated via an infrastructure-to-vehicle (I2V) communication channel, initiating the coordinated movement of the platoon.

A simulation environment was developed to design and evaluate the efficiency of CACC-enabled platooning under the arterial coordinated start concept. The simulation results confirm that the proposed approach effectively enhances the capacity of urban arterial intersections. This method serves as a viable solution for Vehicle Routing Problems (VRPs) by identifying optimal routes for groups of vehicles, thereby reducing travel costs and increasing traffic flow. The improvement is primarily attributed to the reduced inter-vehicle spacing allowed by the CACC system, which maintains safety while enabling more vehicles to pass through the intersection during a single green phase.

However, this study focuses on platoon coordination under relatively idealized conditions. Real-world traffic environments are far more complex and dynamic. Therefore, future research will aim to implement the proposed algorithm on physical hardware and explore its performance in real-world scenarios. This includes developing more robust planning and control strategies that can adapt to diverse and unpredictable traffic conditions.

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